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MONOTONIC AND COMPLETELY REVERSED CYCLIC STRESS-STRAIN AND FATIGUE BEHAVIOR OF REPRESENTATIVE AIRCRAFT METALS

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FOREWORD

This investigation was conducted in the H. F. Moore Fracture Research Laboratories of the Department of Theoretical and Applied Mechanics, University of Illinois in cooperation with the Aeronautical Structures Laboratory of the Naval Air Engineering Center.

This is the final report for Item 1 of Contract No. N-156-46083 covering work done during the period 1 February 1965 through 1 February 1966. Messrs. M. S. Rosenfeld and R. Vining acted as technical liaison for the Navy and Prof. T. J. Dolan, Head of Theoretical and Applied Mechanics furnished administrative and technical guidance.

The authors are indebted to D. H. Williams who did much of the laboratory testing, R. B. Wilson who performed the long life fatigue tests, H. Inoue and R. M. Wetzel for developing the computer program for data processing and to Dr. T. H. Topper and B. I. Sandor who assisted in preparing the manuscript.

SUMMARY

Monotonic and cyclic stress-strain and fatigue behavior in the life range of approximately 10 to 10^5 cycles are experimentally determined for four metals used in aircraft structures. The purpose of this investigation is to establish the necessary materials information and base line fatigue data for later cumulative damage studies employing these same metals.

Stress amplitude under completely reversed strain control is found to increase for 2024-T4 and 7075-T6 aluminum alloys (cyclic hardening) while aircraft quality SAE 4340 steel (quenched and tempered at 1000°F) undergoes cyclic softening. Titanium alloy 811 cyclically hardens slightly during the first few cycles and softens thereafter.

Plots of the fatigue life as a function of elastic, plastic and total strain at half the fatigue life are presented for the four metals. Over the life region between 10 and 10^4 cycles the aluminum alloys have virtually the same life for the same amplitude of total strain. At longer lives the 7075-T6 is slightly superior. In terms of resistance to total strain, Ti 811 is superior to the other three metals and the SAE 4340 steel is between Ti 811 and the aluminum alloys.

The usual log-log linear relationships between fatigue life and the elastic and plastic components of strain do not satisfactorily fit the fatigue results, especially for the two aluminum alloys. Thus, it will be necessary to use the actual fatigue plots rather than simple power functions as the base line fatigue data for future cumulative damage studies.

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I. INTRODUCTION

To predict the fatigue performance of a notched, redundant, spectrum loaded aircraft structure from the results of simple laboratory materials tests requires the following:

a) A knowledge of the cyclic stress-strain and fatigue behavior of the metal of which the structure is fabricated.

b) Mechanics methods for relating the stresses and strains at the most distressed region in the structure to its geometry, the load history, and properties of the metal.

c) A cumulative damage theory to relate the cyclic stresses and strains in the critical region to the fatigue resistance of the metal.

This paper is concerned with establishing the cyclic deformation and fracture properties for representative aircraft structural metals to fulfill the need expressed in a) above. It is a first step towards the broader problem of predicting the fatigue behavior of aircraft structures from simple laboratory materials tests.

II. MATERIALS AND SPECIMENS

Aluminum alloys, 2024-T4 and 7075-T6, aircraft quality SAE 4340 steel and a titanium alloy (Ti 811) were selected as representative aircraft structural metals. Properties of the metals are given in Table 1.

The aluminum and titanium alloys were heat treated by the vendors. Rough machined specimens of the 4340 steel were quenched in oil from 1525 F then tempered at 1000 F for 30 mins. followed by oil quenching.

Two types of specimens were used. The standard specimen shown in Fig. 1-a was 1/4 in. in dia. with a uniform gage length of 3/4 in. Hour-glass specimens shown in Fig. 1-b were used to avoid buckling when the longitudinal strain amplitude was larger than $\pm 1.2\%$.

Aluminum and titanium specimens were machined to the form shown in Fig. 1, and mechanically polished with three successively finer grades of emery. Final machining of the 4340 specimens was done after heat treatment. A surface layer of approximately 0.025 in. was removed from the diameter followed by mechanical polishing with three successively finer grades of emery.

III. APPARATUS AND PROCEDURE

Most tests* were performed on an Instron TTC universal tester with a load capacity of $\pm$ 10,000 lbs. Two head speeds (0.05 inch/min. and 0.2 inch/min.) were used. Strain was measured by an Instron extensometer fastened to the reduced section of the specimen. Strains were measured

*A few of the long life tests were conducted in a Research Inc. Materials Test System.

longitudinally over a gage length of 3/4 of an inch in the straight portion of standard specimens and diametrally at the minimum sections of hourglass specimens. The strain signal was amplified and controlled between limits by a Daytronics unit with limit switches.

The Instron recorder was used to continuously record stress vs. time and a potentiometric X-Y recorder was used to plot stress-strain hysteresis loops.

Special care was taken to avoid clamping distortions in the specimens. This was done by fixing the upper end of the specimen rigidly to the load cell; placing the lower end with a detachable button head into a pot of molten Wood's metal attached to the movable crosshead. The molten metal was then allowed to cool, fixing the lower end of the specimen rigidly to the movable crosshead without clamping distortions.

Test Program: A static tension test to fracture was performed on at least five specimens from each of the four metals. Approximately five companion specimens were tested in fatigue at several completely reversed strain levels for each metal. For each specimen, a continuous record of the cyclic stress was kept and complete hysteresis loops were taken during the first few cycles and periodically thereafter.

Data Reduction: The University of Illinois IBM 1401-7094 computer system* was used to interpret the large number of hysteresis loops obtained in this investigation. The stress range for each loop was divided into sixteen equal increments giving thirty two sets of engineering stress-strain coordinates including the loop tips. These were digitized onto separate IBM cards for each loop to be analyzed. Separate computer programs were used for loops in terms of diametral strains and those in terms of longitudinal strains.

For diametral strain tests, the true longitudinal stress, σ, was calculated for each point on the loop from the engineering diametral strain, e_d, and the nominal engineering stress, S, using the following equation:

$$\sigma = S\ (1 + e_d)^{-2}$$

The linear unloading portion of the stress-diametral strain loop has a slope equal to the modulus of elasticity, E, divided by the elastic Poisson's ratio, μ_e, permitting the value of μ_e to be calculated. The elastic unloading lines were extrapolated to the opposite stress limit so that each strain coordinate could be separated into linear elastic and nonlinear plastic strain components. By dividing the elastic component by μ_e and the plastic component by the plastic Poisson's ratio, μ_p, which is equal to 0.5 for constancy of volume, the engineering longitudinal elastic strain, e_e, and plastic strain, e_p, are obtained. These are added to obtain the total longitudinal strain, e.

True longitudinal total strain, ϵ, elastic strain, ϵ_e, and plastic strain, ϵ_p, are calculated using the following equations:

$$\epsilon = \ln(1 + e)$$

*Partially supported by a grant from the National Science Foundation, NSFGP 700.

$$\epsilon_e = \sigma / E$$

$$\epsilon_p = \epsilon - \epsilon_e$$

The same equations were used in the program for engineering stress-longitudinal strain loops with the true stress calculated from the following equation:

$$\sigma = S\,(1 - \mu_e\, e_e - \mu_p\, e_p)^{-2}$$

The plastic strain hysteresis energy, ΔW, or the area inside of each σ-ϵ loop was calculated using Simpson's rule and appropriate geometric operations.

IV. EXPERIMENTAL RESULTS

Due to cyclic hardening or softening, the stress, elastic strain and plastic strain range change during cycling under constant total strain control conditions. Figures 2 thru 5 show the manner in which the stress cyclically changes at different strain amplitudes for the four metals.

It is seen that the cyclic rate of change of stress is minimal after 20 to 50% of the fatigue life. It was found that the variation in deformation resistance and life from specimen to specimen at the same strain level was quite small. Therefore, only average values of stable stress level, and other characteristics of individual loops at approximately half the fatigue life are reported in Tables 2 thru 5 for each strain level investigated. The reported fatigue life is the arithmetic mean life. The small scatter observed in fatigue life can be seen in Figs. 6 thru 9.

The representative stable values of plastic, elastic and total strain from Tables 2 thru 5 are plotted versus life in Figs. 10 thru 13.

By connecting the tips of stable loops from several tests at different strain ranges, a smooth curve is formed, which is called the cyclic stress-strain curve (1). The curve can be expressed mathematically by a power relationship for nearly all metals. This means that there will be a log-log linear relationship between cyclic stress and plastic strain in the stable condition as shown in Fig. 14, for the four aircraft metals. The slope of the line is called the cyclic strain hardening exponent, n'. Values of n' for the four metals are given in Fig. 14.

V. DISCUSSION OF RESULTS

The two aluminum alloys cyclically harden and 4340 steel in this condition cyclically softens, while the titanium alloy, particularly for large strain amplitudes, exhibited cyclic hardening early in the test, followed by cyclic softening.

The titanium alloy exhibited anisotropic deformation behavior causing the minimum section of specimens tested in tension to become oval shaped instead of circular. Also, diametral deformation at the minimum section of hourglass specimens differed greatly depending upon the orientation of the extensometer. This anisotropy is believed to be partially responsible for the observed large scatter in fatigue life for the titanium samples when diametral strain was controlled (see left portion of Fig. 9).

Fatigue Life in Terms of Cyclic Strains: Average fatigue life is plotted versus half life values of plastic, elastic and total strain in Figs. 10 thru 13 in the manner suggested by Manson and co-workers (2, 3). For a number of metals, linear relationships between both plastic and elastic strain and the fatigue life are found on this type of plot. Where this is sufficiently correct, the following equation describes the total strain-life relationship:

$$\frac{\Delta\epsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \epsilon'_f\,(2N_f)^c \quad \text{------------ (1)}$$

In Ref. (1), the constants, b, c, σ'_f and ϵ'_f are looked upon as fatigue properties of the metal and defined as follows:

- σ'_f = Fatigue strength coefficient, the intercept of the log σ_a - log $2N_f$ plot at one reversal or $2N_f = 1$, σ'_f/E is the elastic strain when $2N_f = 1$ or the intercept points for the log $\Delta\epsilon_e/2$ vs log $2N_f$ portion of plots such as Figs. 10 thru 13.
- b = Fatigue strength exponent, the slope of the log $\Delta\epsilon_e/2$ vs log $2N_f$ plot.
- ϵ'_f = Fatigue ductility coefficient, the intercept of the log $\Delta\epsilon_p/2$ vs log $2N_f$ plot at $2N_f = 1$.
- c = Fatigue ductility exponent, the slope of the log $\Delta\epsilon_p/2$ vs log $2N_f$ plot.

It was our original intention in this program to determine the magnitude of the above fatigue properties for each of the four metals. However, as can be seen from Figs. 10 and 11, it is unrealistic to attempt to force straight lines through the elastic and plastic strain versus life lines for the aluminum alloys. The experimental lines are not straight on the log-log plot but are curved with a downward concavity. The values of the coefficients, σ'_f and ϵ'_f in Eq. (1) can usually be approximated by the monotonic true fracture strength, σ_f, and ductility, ϵ_f. Monotonic test values are shown in these figures at one reversal and are seen to poorly correspond with the intercept at one reversal of any reasonable straight line placed through the fatigue data points.

Looking at Figs. 12 and 13 it can be seen that the steel and titanium more nearly conform to the straight line concepts and that the monotonic fracture points are reasonable approximations to the intercepts at one reversal. However, the steel and titanium data also exhibit the tendency toward downward concavity in the elastic and plastic strain versus life

lines, though to a lesser degree than in the case of the aluminum alloys.

Many factors have been considered which might account for the observed deviations from linearity. These include possible differences between strain measuring techniques for hourglass specimens used at high strains and standard specimens used at low strains, the difference in volume of highly stressed material between the hourglass and longitudinal specimens, the possibility of misalignment and bending stresses in the low strain tests and other factors. None of the factors considered seemed to be capable of quantitatively accounting for the observed deviations.

A number of tests were repeated, but essentially the same results were obtained. A check of the literature revealed that the same type of "arched" curves have been obtained by others (2,4,5,6), for similar aluminum alloys. As a matter of fact, the reported results in these references are practically coincident with our results.

Low cycle fatigue data reported in Refs. (2) and (3) on two conditions of 4340 steel agree closely with the present results. To our knowledge there is no similar data in the literature for Ti 811 with which to compare our results.

An attempt was made to fit the total strain versus life data with an equation of the form of Eq. (1) even though the coefficients and exponents might not necessarily correspond to intercepts and slopes of elastic and plastic strain versus life lines. This was unsuccessful since curves obtained from functions of the form of Eq. (1) gradually change curvature in the transition fatigue life region (where elastic and plastic strains are equal) while the experimental curves for total strain versus life are nearly straight between approximately 10 and 10^3 cycles and abruptly change slope to a lower constant value at long lives.

Considering the main purpose of this work which is to furnish the completely reversed constant amplitude data for later research on cumulative damage, it was decided to simply present the life data in tabular form and in the form of the life plots shown in Figs. 10 thru 13, without attempting to express the results in analytic form at this time. This means that it will be necessary to refer to the actual strain-life plots for base line fatigue data.

<u>Comparison of the Four Metals:</u> It is worth noting that the total strain versus life curves for the two aluminum alloys (Figs. 10 and 11) are virtually the same between 10 and 10^4 cycles. Thus, these two alloys will probably perform about the same in structures subjected to low cycle fatigue. However, at long lives the 7075-T6 has a larger resistance to cyclic strain than does the 2024-T4.

Titanium 811 exhibits the largest resistance to cyclic strain over the entire life region studied, while the SAE 4340 is between the titanium and aluminum alloys.

VI. CONCLUSIONS

Monotonic and completely reversed cyclic strain tests on four representative aircraft metals permit the following conclusions to be drawn.

1) Cyclic hardening takes place under strain control for 2024-T4 and 7075-T6 aluminum alloys.

2) Cyclic softening occurs for quenched and tempered SAE 4340 heat treated to an ultimate strength of about 180 ksi.

3) Titanium 811 hardens slightly, then softens due to strain cycling.

4) The usual linear log-log relations between fatigue life and elastic and plastic strain do not satisfactorily describe the fatigue results for the two aluminum alloys, but fit the steel and Ti 811 fatigue data reasonably well.

5) For the above reason it will be necessary to use actual fatigue data plots rather than simple power functions to describe the fatigue resistance of these metals especially if they are to be used in a study of cumulative damage.

6) In terms of fatigue resistance to completely reversed total strain, the two aluminum alloys are equivalent in the life region between 10 and 10^4, Ti 811 has lives approximately a factor of four larger than the aluminums for the same cyclic strain, and the SAE 4340 is between the titanium and aluminum alloys.

VII. REFERENCES

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6. R. D'Amato and R. De Boer, "A Study of the Relationship Between Notched and Unnotched Specimens of 2024 Aluminim Alloy in the Low-Cycle Fatigue Regime," Wright-Air Development Center Technical Note 59-2, Wright-Patterson Air Force Base, Ohio, May 1959.

TABLE 1-a DESCRIPTION OF MATERIALS

Designation	2024-T4 Al Alloy	7075-T6 Al Alloy	Aircraft Qual. SAE 4340 Steel	Titanium 811
Nominal Chem. Comp. Percent	Si-0.50, Fe-0.50 Cu-3.7 - 4.9 Mn-0.3 - 0.9 Mg-1.2 - 1.8 Cr-0.10, Zn-0.25 Others-0.05 Al-Balance	Si-0.50, Fe-0.70 Cu-1.2 - 2.0 Mn-0.30 Mg-2.1 - 2.9 Cr-0.18 - 0.40 Zn-5.1 - 6.0 Ti-0.20 Al-86.75 /89.57	C-0.43, Mn-0.71 P-0.010, S-0.013 Si-0.24, Cr-0.86, Ni-1.79, Mo-0.27 Cu-0.09 Fe-Balance	Al-7.9, Mo-1.0 V-1.1, C-0.02 N-0.007, Fe-0.06 O-0.087 H-119 (ppm) Ti-Balance
Source of Bar Stock	Reynolds via Castle & Co. Chicago	Reynolds via Castle & Co. Chicago	Crucible via Castle & Co. Chicago Heat No. 136820	Reactive Metals Niles, Ohio Heat No. 291976
Condition	3/4" dia. rd. (rolled) T4 heat treatment	3/4" dia. rd. (rolled) T6 heat treatment	3/4" dia. rd. quench & temp to approx. S_u = 180 ksi	0.675" dia. rd. duplex anneal

TABLE 1-b PROPERTIES OF MATERIALS

Designation	2024-T4 Al Alloy	7075-T6 Al Alloy	Aircraft Qual. SAE 4340 Steel	Titanium 811
Mod. of Elast. ksi, E	10,200	10,300	28,000	17,000
0.2% Offset Y. S. ksi, S_{ty}	44	68	171	146
Ult. Strength, ksi, S_u	69	84	180	148
% RA	35	33	57	48
True Fracture Ductility, ϵ_f	0.43	0.41	0.84	0.66
True Fracture Strength, ksi, σ_f^*	99/91.5	116/108	277/240	239/215
Strain Hard. Exp., n	0.20	0.113	0.066	0.078
Strength Coeff. ksi, K	117	120	229	193

Note: The properties reported are averages of at least five tests on 0.25" dia. specimens.

* Upper value is P_f/A_f, lower value is corrected for necking using Bridgman's method.

TABLE 2 SUMMARY OF RESULTS--2024-T4 ALUMINUM, VALUES ARE AVERAGES OF SEVERAL TESTS

No. of Spec.	Cycles to Failure N_f	Diametral Strain Range	Characteristics of the Stable Hysteresis Loop				Work to Fracture, W_f, ksi
			$\Delta\epsilon$	$\Delta\epsilon_p$	$\Delta\sigma$, ksi	ΔW, ksi	
2	5	0.0697	0.145	0.128	177	20.3	96
5	14	0.0423	0.089	0.072	172	11.4	163
5	45	0.0271	0.058	0.043	162	6.3	278
5	142	0.0162	0.0365	0.0218	152	3.0	419
6	310		0.0245	0.0104	136	1.2	400
5	1000		0.0164	0.0039	129	0.43	407
5	4200		0.0112	0.0003	114		
5	12400		0.0093		98		

TABLE 3 SUMMARY OF RESULTS -- 7075-T6 ALUMINUM, VALUES ARE AVERAGES OF SEVERAL TESTS

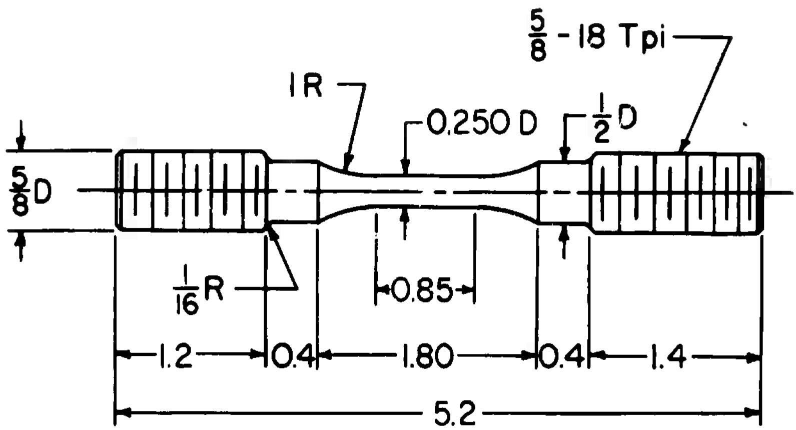
No. of Spec.	Cycles to Failure, N_f	Diametral Strain Range	Characteristics of the Stable Hysteresis Loop				Work to Fracture, W_f, ksi
			$\Delta\epsilon$	$\Delta\epsilon_p$	$\Delta\sigma$, ksi	ΔW, ksi	
5	4	0.0697	0.145	0.125	207	22.7	100
5	13	0.0427	0.090	0.071	200	12.9	167
5	44	0.0266	0.058	0.040	192	6.9	300
5	131	0.0157	0.037	0.020	176	3.2	414
5	323		0.0241	0.008	156	1.1	338
5	1000		0.0158	0.0013	146	0.18	194
4	3360		0.0125		131		
2	4660		0.0113		122		

TABLE 4 SUMMARY OF RESULTS -- SAE 4340 STEEL, VALUES ARE AVERAGES OF SEVERAL TESTS

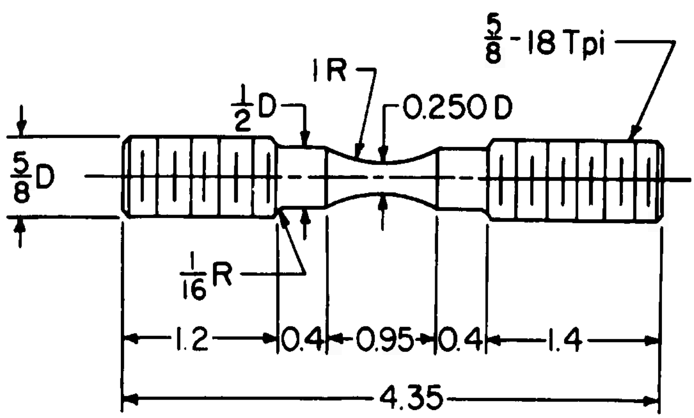
No. of Spec.	Cycles to Failure N_f	Diametral Strain Range	Characteristics of the Stable Hysteresis Loop				Work to Fracture, W_f, ksi
			$\Delta\epsilon$	$\Delta\epsilon_p$	$\Delta\sigma$, ksi	ΔW, ksi	
5	10	0.117	0.240	0.225	407	79	774
5	17	0.079	0.160	0.147	370	46	847
5	74	0.043	0.090	0.077	356	23	1700
5	167	0.0274	0.058	0.046	323	12	2000
5	477		0.024	0.014	272	2.8	1340
5	957		0.021	0.012	257	2.1	1990
5	5360		0.0098	0.0022	222	0.34	2000+
3	64600		0.0064		165		

TABLE 5 SUMMARY OF RESULTS--TITANIUM 811, VALUES ARE AVERAGES OF SEVERAL TESTS

No. of Spec.	Cycles to Failure, N_f	Diametral Strain Range	Characteristics of the Stable Hysteresis Loop				Work to Fracture W_f, ksi
			$\Delta\epsilon$	$\Delta\epsilon_p$	$\Delta\sigma$, ksi	ΔW, ksi	
5	37	0.0734	0.154	0.132	346	42	2100
3	74	0.0417	0.090	0.071	326	20	1090
3	383	0.0178	0.043	0.025	297	6.4	2400
5	1520		0.024	0.010	238	1.9	2800
5	4360		0.016	0.004	223	0.8	2500
3	92700		0.0096				



a) Standard Specimen (3/4 Inch Gage Length)



b) Hourglass Specimen

Fig. 1 Specimen Dimensions

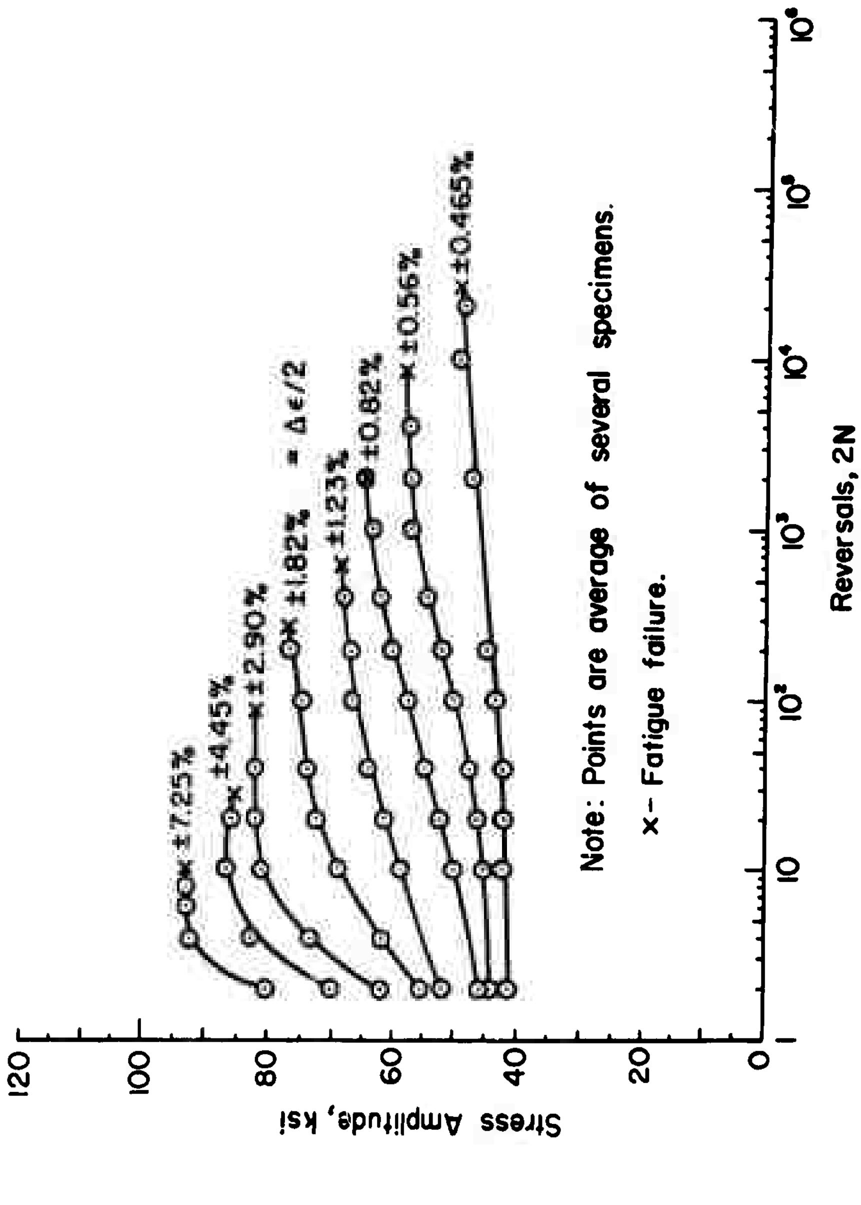


Fig.2 Stress Change During Reversed Strain Cycling – 2024-T4 Aluminum

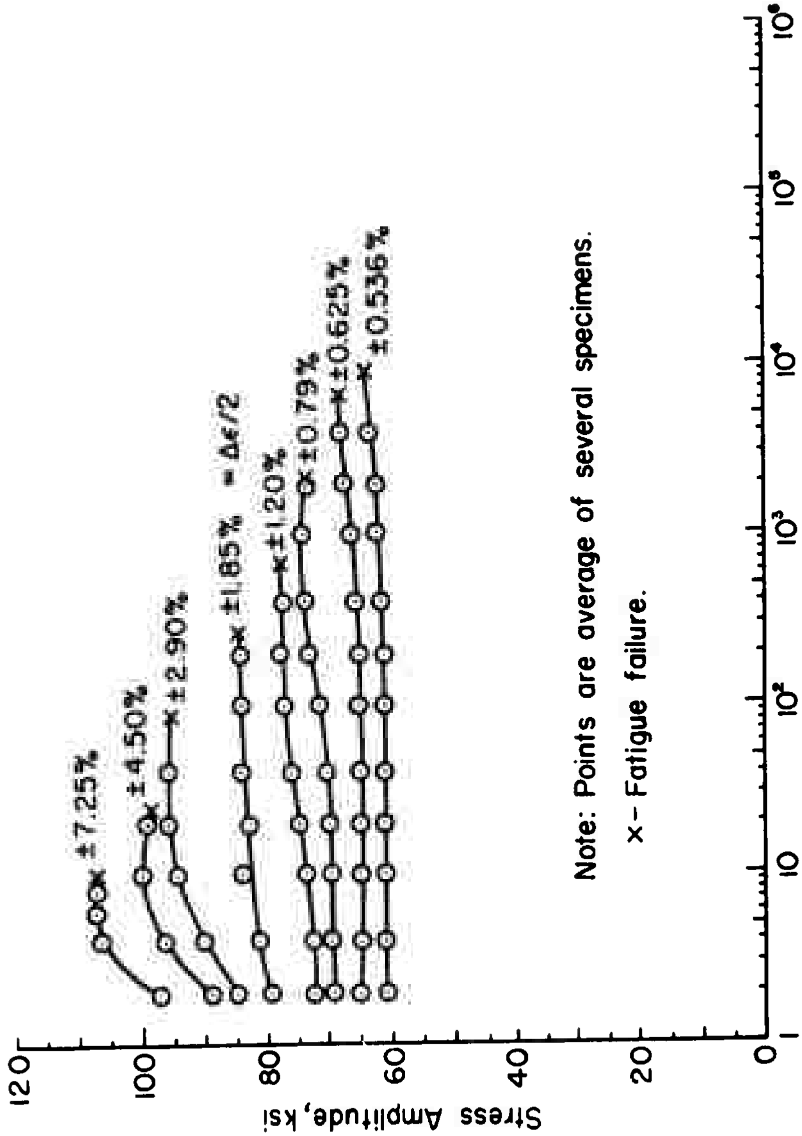


Fig. 3 Stress Change During Reversed Strain Cycling – 7075-T6 Aluminum

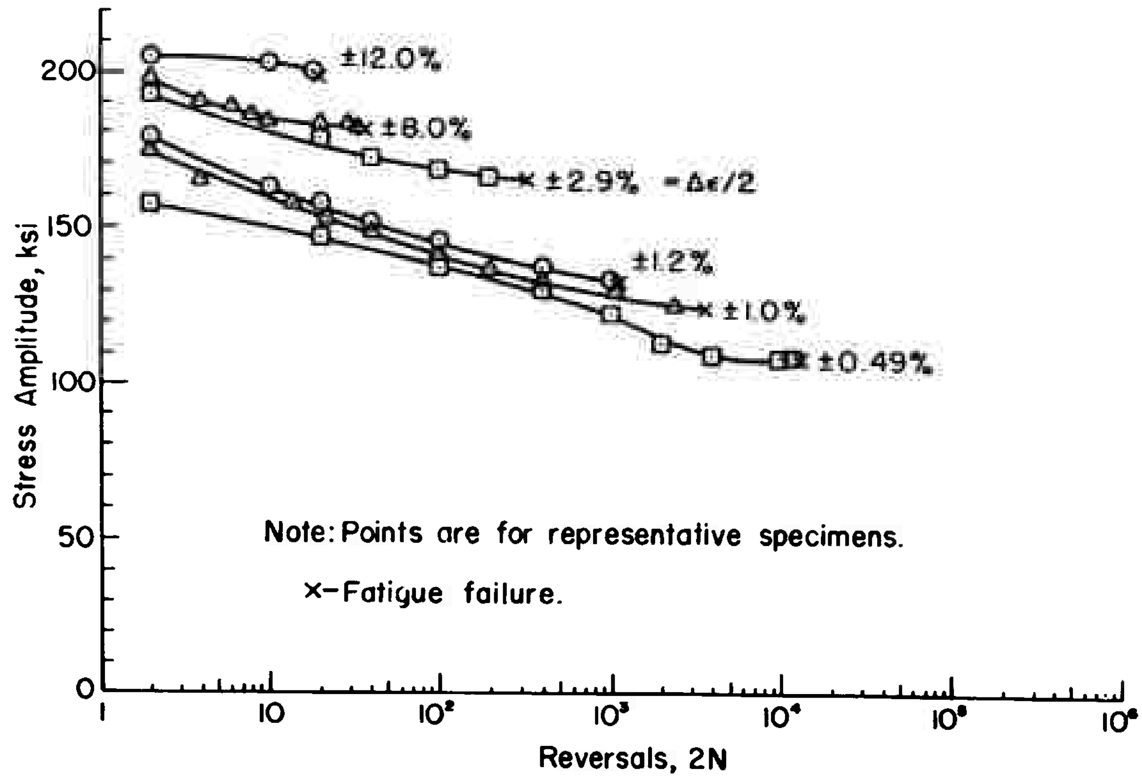


Fig. 4 Stress Change During Reversed Strain Cycling – SAE 4340 Steel

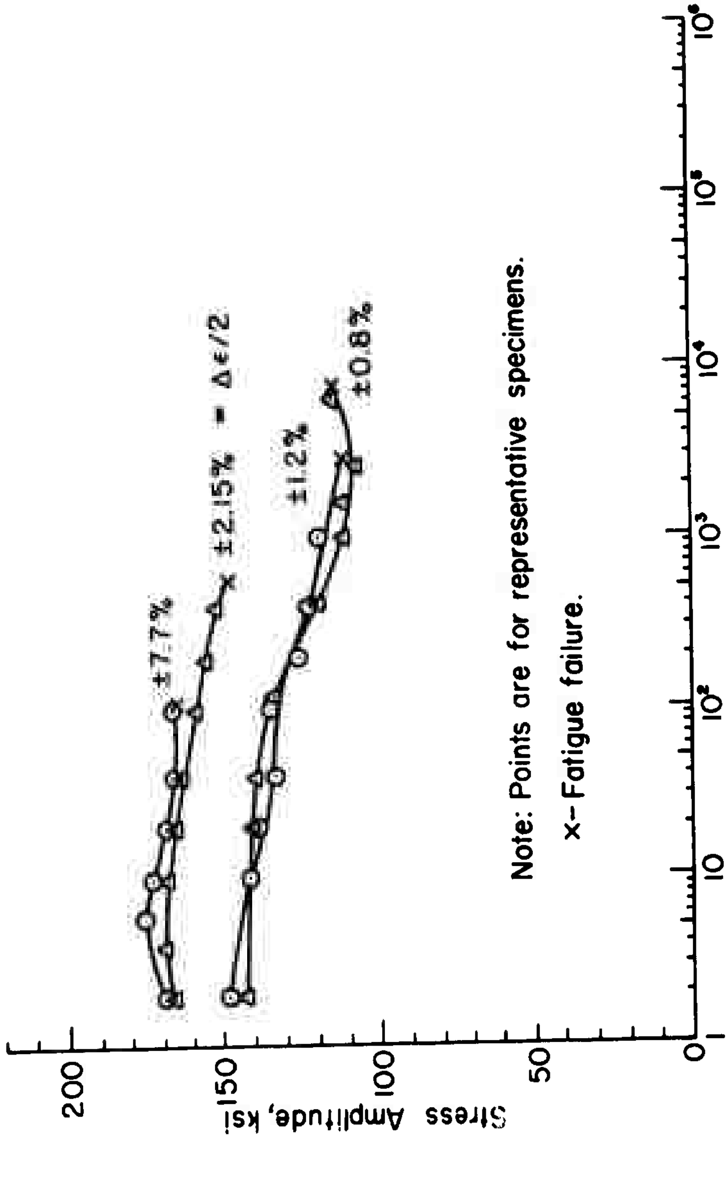


Fig. 5 Stress Change During Reversed Strain Cycling — Titanium 811

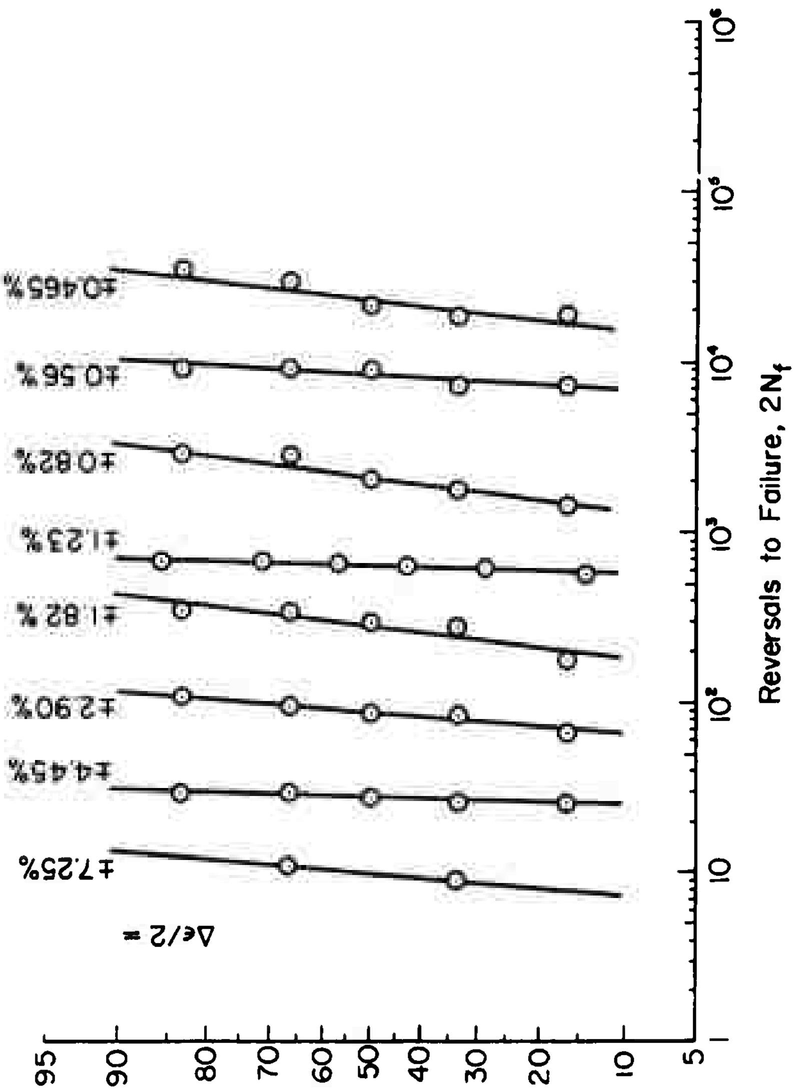


Fig.6 Scatter in Fatigue Life for Completely Reversed Strain Cycling – 2024-T4 Aluminum

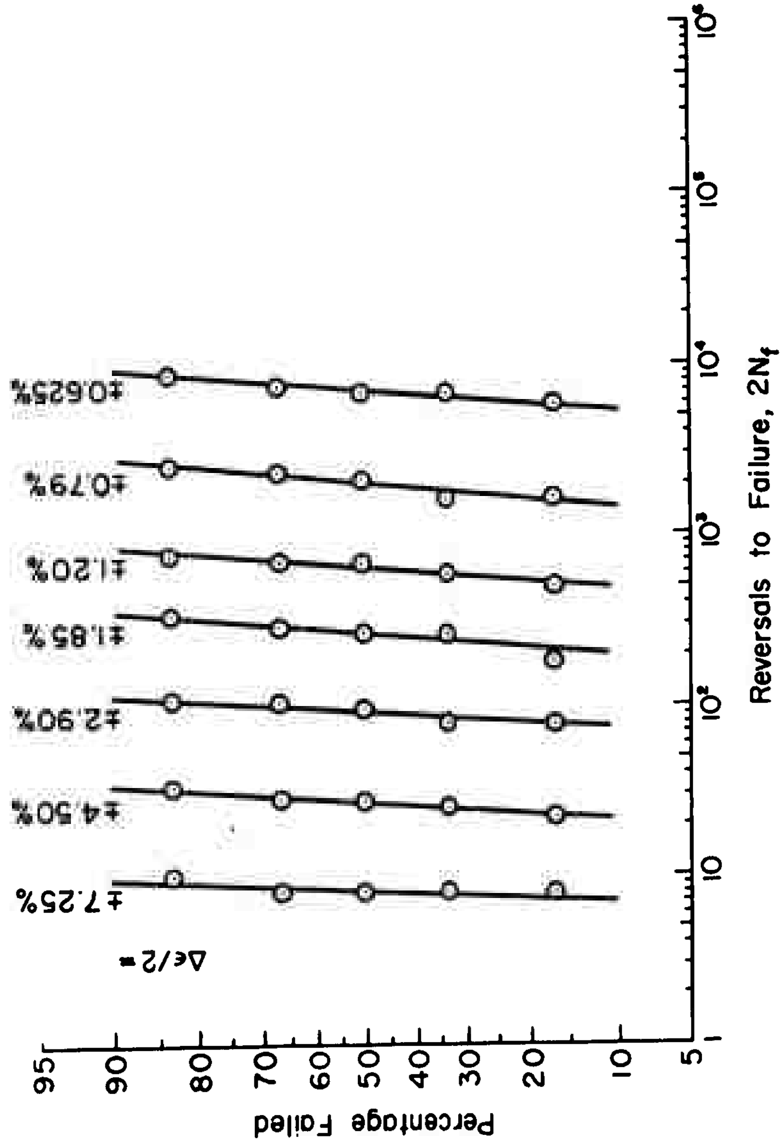


Fig. 7 Scatter in Fatigue Life for Completely Reversed Strain Cycling – 7075-T6 Aluminum

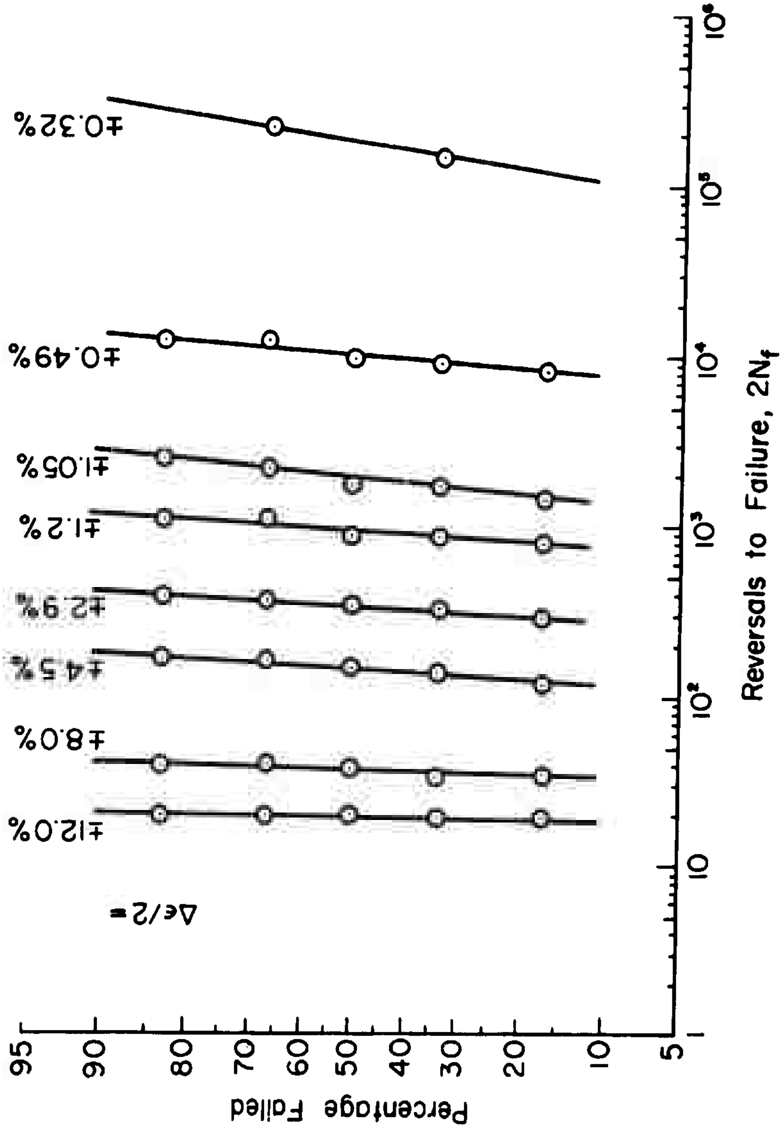


Fig.8 Scatter in Fatigue Life for Completely Reversed Strain Cycling – SAE 4340 Steel

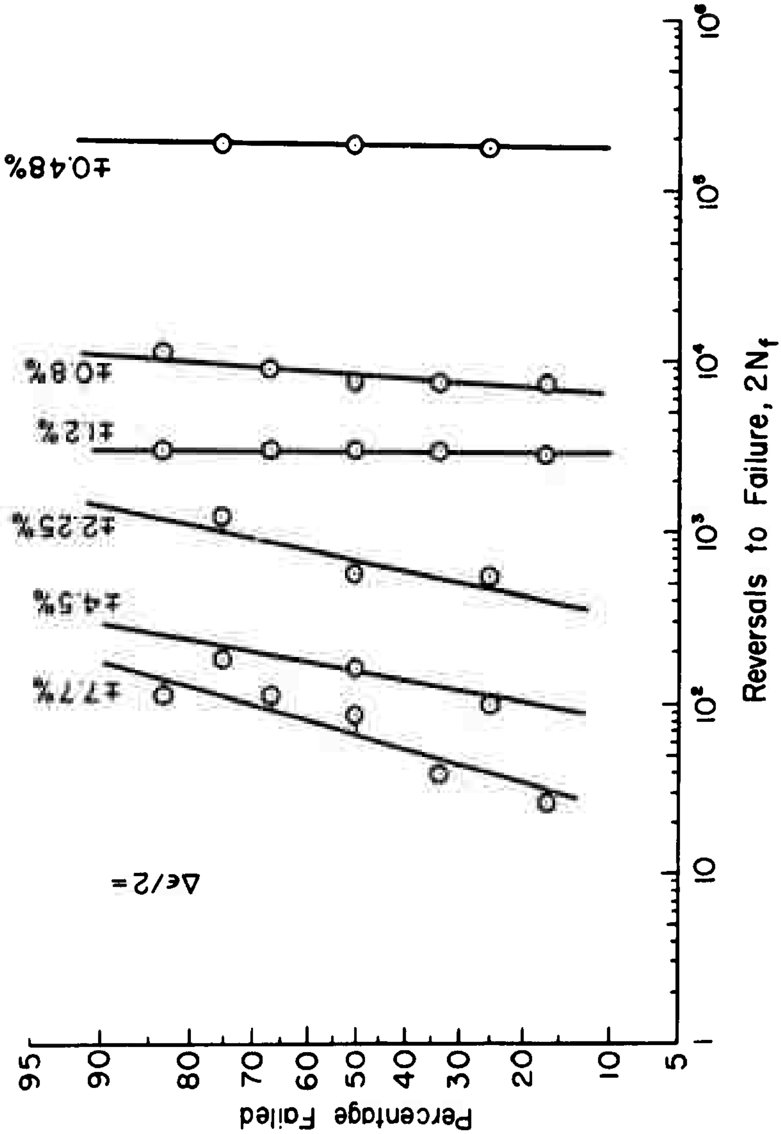


Fig.9 Scatter in Fatigue Life for Completely Reversed Strain Cycling – Titanium 811

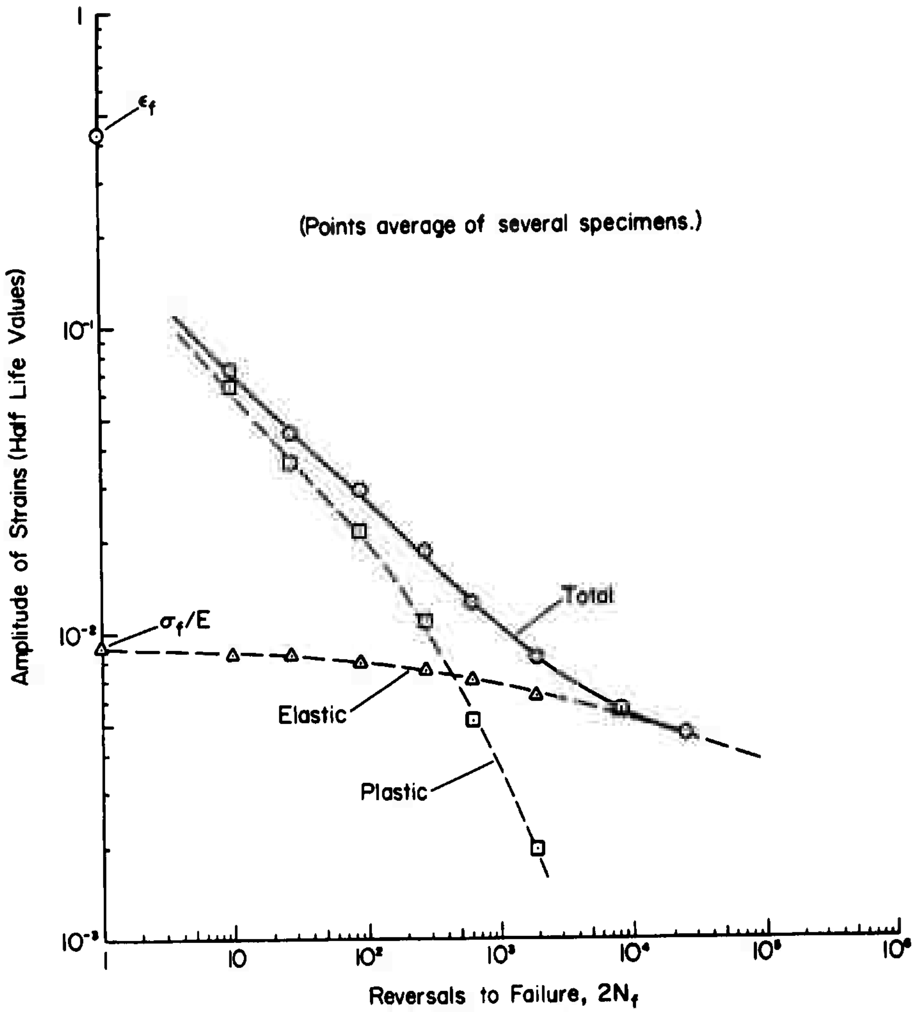


Fig. 10 Life as a Function of Elastic, Plastic and Total Strain-
2024-T4 Aluminum.

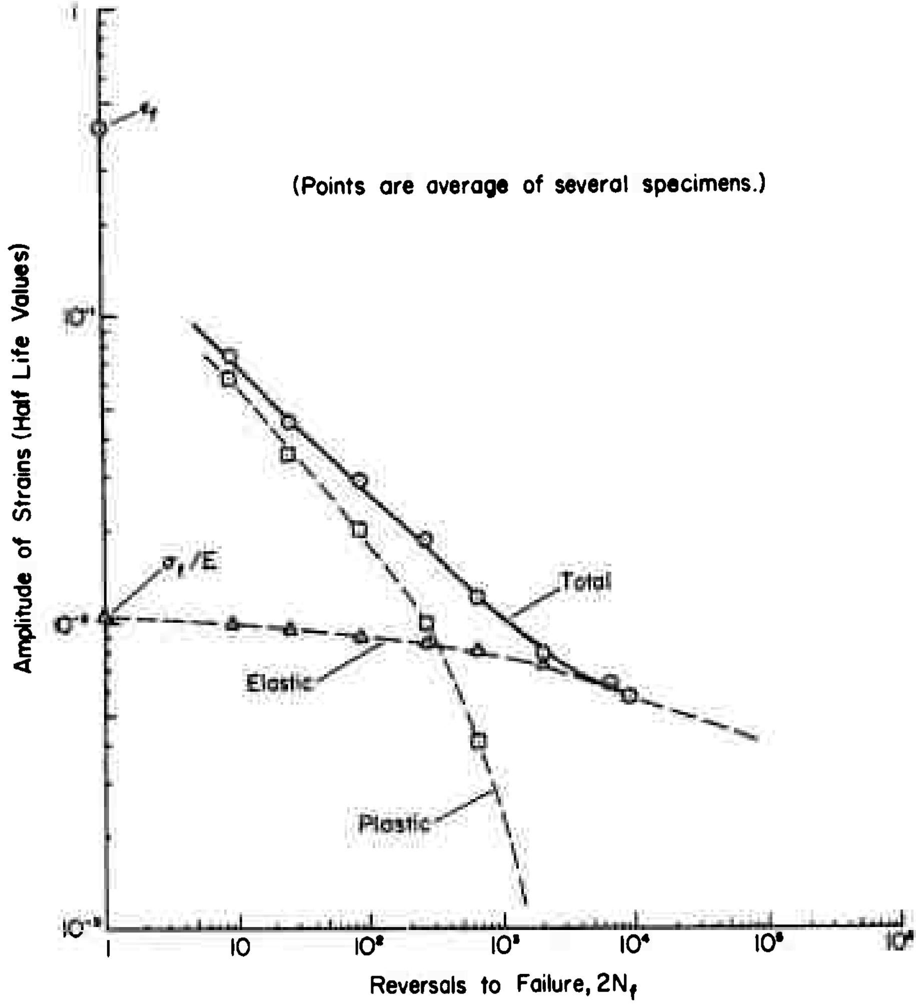


Fig. 11 Life as a Function of Elastic, Plastic and Total Strain - 7075-T6 Aluminum.

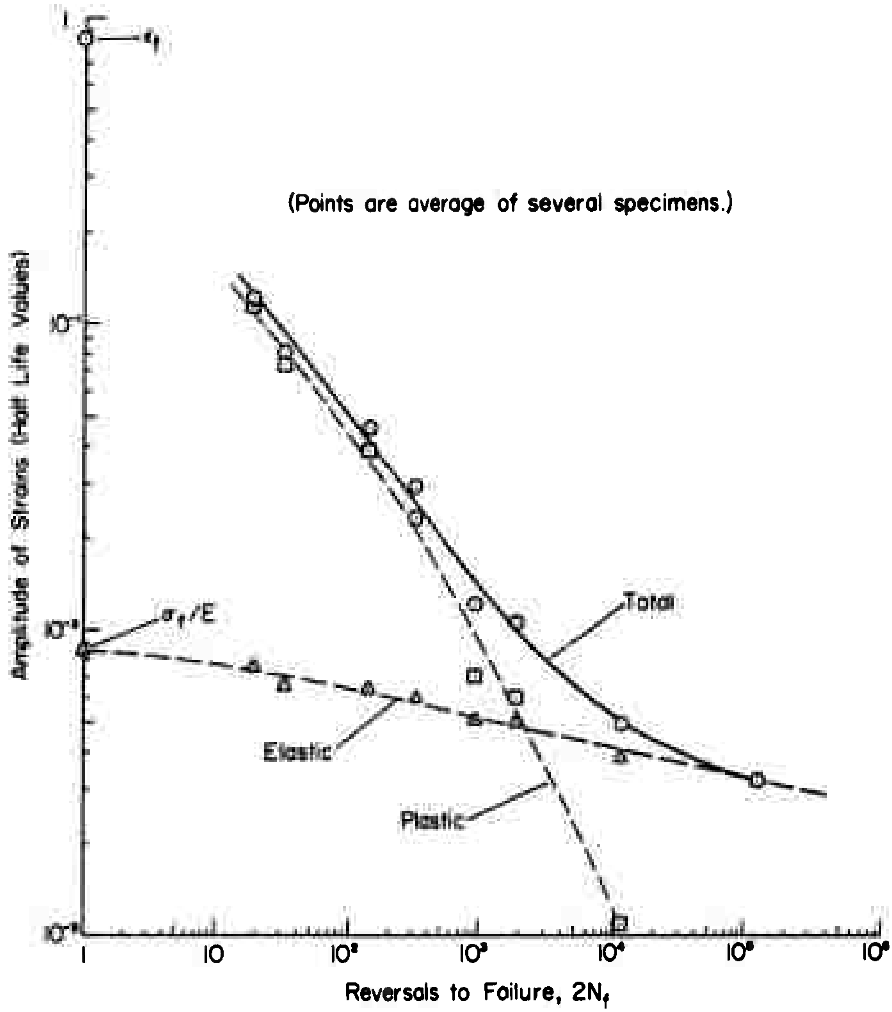


Fig. 12 Life as a Function of Elastic, Plastic and Total Strain-
SAE 4340 Steel.

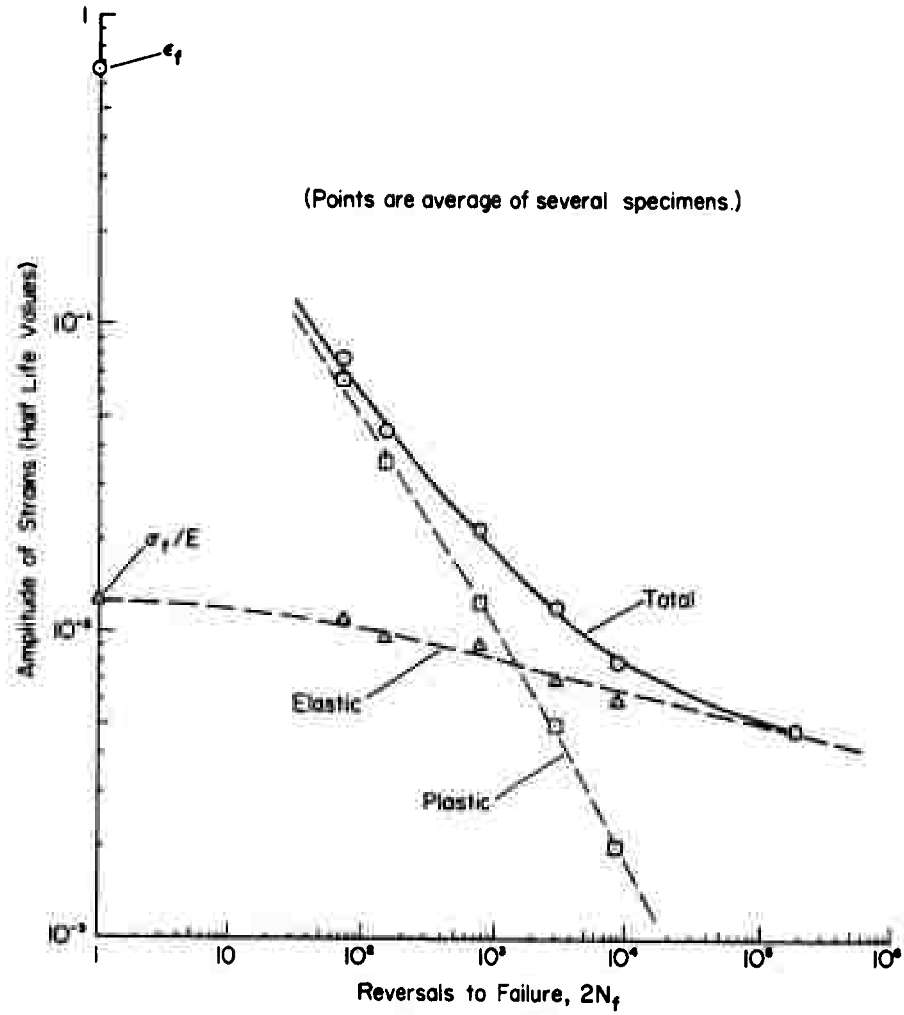


Fig. 13 Life as a Function of Elastic, Plastic and Total Strain – Titanium 811.

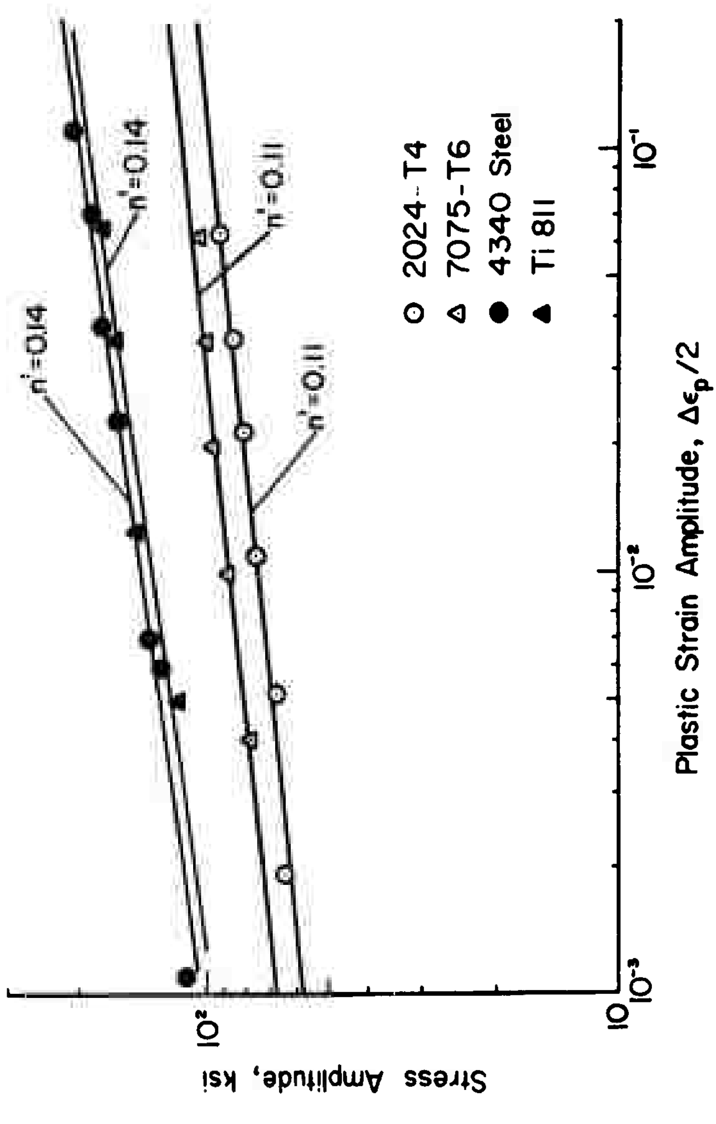


Fig. 14 Cyclic Stress – Plastic Strain

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13 ABSTRACT

Monotonic and cyclic stress-strain and fatigue behavior in the life range of approximately 10 to 10^5 cycles are experimentally determined for 2024-T4 and 7075-T6 aluminum alloys, SAE 4340 steel (quenched and tempered at 1000°F), and titanium alloy 8-1-1. The purpose of this investigation is to establish the necessary materials information and base line fatigue data for cumulative damage studies. Plots of the fatigue life as a function of elastic, plastic and total strain at half the fatigue life are presented for the four metals. The usual log-log linear relationships between fatigue life and the elastic and plastic components of strain do not satisfactorily fit the fatigue results, especially for the two aluminum alloys. Thus, it will be necessary to use the actual fatigue plots rather than simple power functions as the base line fatigue data for cumulative damage studies.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Metals Fatigue Controlled strain cycling Cyclic stress-strain Tensile properties						

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